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J06587−5558 — A Very Unusual Polarised Radio Source

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ABSTRACT

We have found a peculiar radio source J06587−5558 in the field of one of the hottest known clusters of galaxies 1E0657−56. It is slightly extended, highly polarised (54% at 8.8 GHz) and has a very steep spectrum, with $\alpha \sim -1$ at 1.3 GHz, steepening to ~ -1.5 at 8.8 GHz ($S \propto \nu^{\alpha}$). No extragalactic sources are known with such high integrated polarisation, and sources with spectra as steep as this are rare. In this paper, we report the unusual properties of the source J06587−5558 and speculate on its origin and optical identification.

Key words: galaxies: clusters: individual (1E0657−56 (RXJ0658−5557)) — galaxies: intergalactic medium— radio continuum: general —X-rays: general

1 INTRODUCTION

The cluster 1E 0657−56 at $z \sim 0.296$ is in many ways exceptional. It has a high X-ray luminosity $L_{\rm bol} \sim 1.4 \times 10^{46}$ erg s^{-1}, and it is a contender for being the hottest known cluster ($kT_X \sim 14.5$ keV; Tucker et al. 1998, Liang et al. 2000). The ROSAT PSPC/HRI images show that the cluster has two distinct X-ray subclumps indicating on-going merging activity (Fig. 1). Owing to its high X-ray luminosity, the cluster was chosen for the detection of the Sunyaev-Zel'dovich effect with the Swedish ESO Submillimeter Telescope (SEST; Andreani et al. 1999). The SEST detection of the Sunyaev-Zel'dovich effect in the cluster prompted subsequent attempts to confirm the detection at centimetre wavelengths at the Australia Telescope Compact Array (ATCA). However, any Sunyaev-Zel'dovich decrement at centimetre wavelengths was masked by the presence of one of the most powerful cluster-wide diffuse radio haloes known (Liang et al. 2000). The radio halo is believed to be of synchrotron emission and has an extent and morphology similar to the X-ray emission. When searching for possible polarisation in the radio halo, we found an unusual highly polarised discrete source, J06587−5558, about 2.5 arcmin from the cluster centre.

We discuss the nature of the source in the following sections. In section 2, we briefly describe the radio properties of the source; in section 3, we explore the possibilities of it being Galactic or extragalactic; sections 4 and 5 discuss whether it is inside or behind the cluster; section 6 gives the results of deep imaging with the VLT, and the conclusions are given in section 7.

Throughout the paper we will assume $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 75\,{\rm km\,s^{-1}\,Mpc^{-1}}$.

2 A PECULIAR RADIO SOURCE

Radio observations centred on the cluster 1E 0657−56 were obtained at the ATCA using various antenna configurations and observing frequencies. The observations were aimed initially at the attempted detection of the Sunyaev-Zel'dovich effect, subtraction of confusing radio sources and subsequent studies of the radio halo emission. Details of the radio observations are given in Liang et al. (2000). The peculiar radio source J06587−5558 stands out in the polarisation maps with $\sim 54\%$ linear polarisation at 8.8 GHz. It is significantly depolarised with $< 0.5\%$ polarisation at 1.3 GHz. No circular polarisation was detected, with an upper limit of 0.5% at 1.3 GHz. The source has a steep spectrum, with a spectral index (defined by $S \propto \nu^{\alpha}$) of $\alpha^{1.3\,{\rm GHz}}_{2.2\,{\rm GHz}} = -1.0$, steepening at higher frequencies to reach $\alpha^{4.8\,{\rm GHz}}_{8.8\,{\rm GHz}} = -1.5$ (Fig. 2). The properties of the source are summarised in Table 1.

The spectrum and polarisation suggest that the emission is synchrotron. Synchrotron emission is intrinsically highly polarised (up to $\sim 70\%$), but observed polarisations are usually weak due to various depolarisation effects. While a small region (e.g. part of a jet) of an extragalactic source can be highly polarised, so far no extragalactic radio source is known with such a high *integrated* linear polarisation (e.g. de Zotti et al. 1999), and only a few percent of the sources found at high radio frequencies have spectra as steep as J06587−5558 (e.g. Richards 2000).

3 GALACTIC OR EXTRAGALACTIC?

Radio emission with such high polarisation and such a steep spectrum is normally seen only from pulsars; in fact, the millisecond pulsars were discovered this way. A high resolution follow-up observation obtained with the ATCA in 1997 November using the 6C

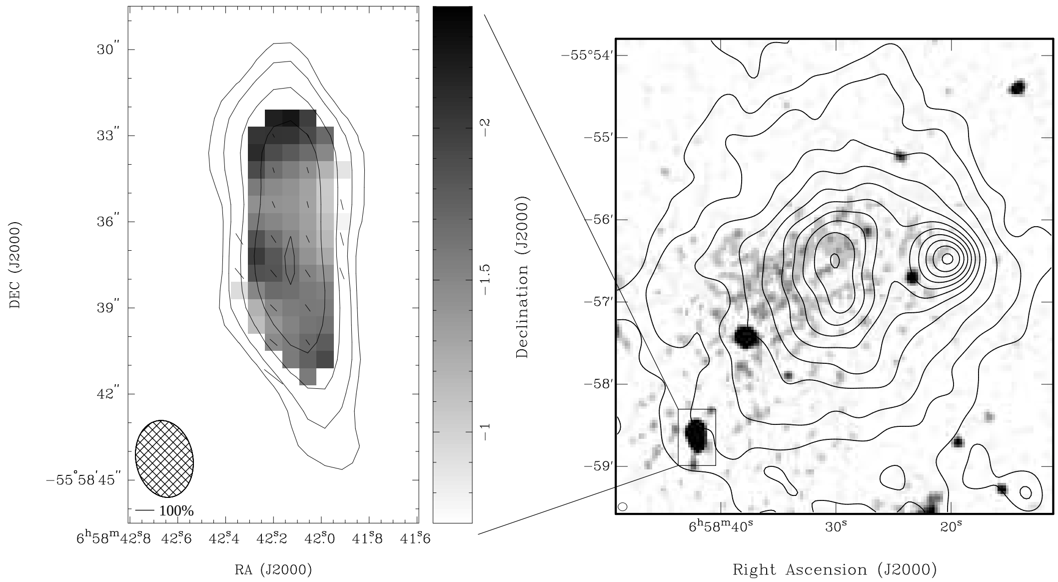

Figure 1. *Left:* 4.8 GHz total intensity contour map overlaid on a grey scale spectral index (4.8–8.8 GHz) image of J06587−5558. The contours are $(3, 6, 12, 24, 48) \times \sigma$, where $\sigma = 40\mu$Jy is the rms noise in the image. The vectors represent the observed E-vectors of the polarised emission at 4.8 GHz and have not been rotated back to their intrinsic position angles. The length of each vector corresponds to the fractional linear polarisation; the length of the vector corresponding to 100% polarisation is given in the bottom left hand corner together with the synthesised beam ($2.7'' \times 2.0''$). The possible optical counterpart discussed in section 6 is marked with a cross. *Right:* A radio/X-ray overview of the field of the cluster 1E 0657−56. The grey scale radio image at 1.3 GHz has a resolution of $6.5'' \times 5.9''$; the beam is shown in the bottom left hand corner. The X-ray contours are from a *ROSAT* HRI image smoothed with a Gaussian of $10''$ FWHM. The contour levels are 0.35, 0.45, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.2 HRI cts s^{-1}.

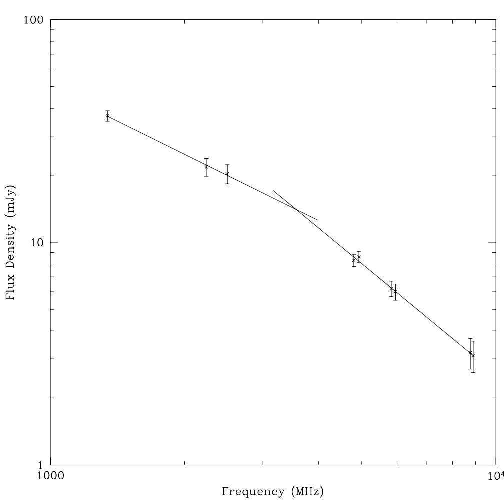

Figure 2. Total radio flux density versus frequency. The low frequency spectral index is -1 and the high frequency index is -1.5, implying a spectral break in the region of 3–4 GHz.

configuration at 4.8 and 8.8 GHz showed that the source was elongated by $\sim 15'' \times 4.5''$ (Figs 1 & 3). The deconvolved elliptical Gaussian size of the source is $\sim 7.8'' \times 1.8''$ FWHM at all frequencies from 1.3 to 8.8 GHz. Since the source is extended, and by a similar amount at all frequencies, it cannot be a pulsar, or even a scattered pulsar. The agreement in angular size also indicates that there is no significant systematic loss of short-spacing flux at high frequencies, so the steepening of the spectrum in Fig. 2 is real.

If Faraday rotation is caused by the external media between the source and the observer, then the position angle of the electric vector (Φ) is related to wavelength (λ) by

$$\Phi = \Phi_0 + (\mathrm{RM})\lambda^2 \qquad (1)$$

where RM is the rotation measure. The position angle versus λ^2 relation is well fitted by a straight line to five frequencies spanning the range 2.2–8.9 GHz. Between 4.8 and 8.8 GHz, at a resolution of $2.7'' \times 2.0''$, we obtain an average rotation measure of $-266 \pm 37\,\mathrm{rad\,m^{-2}}$ across the source. Figure 3 shows the rotation measure across the source in greyscale. For comparison, the Galactic rotation measure in the direction of the source is $\sim +64\,\mathrm{rad\,m^{-2}}$ (Simard-Normandin et al. 1981), or $+36 \pm 28\,\mathrm{rad\,m^{-2}}$ (J. Han, private communication). Hence, the rotation measure in J06587−5558 is unlikely to be Galactic in origin, and this, together with the absence of a clear optical counterpart (see section 6), argues that the source must be extragalactic.

4 INSIDE THE CLUSTER?

The ESO 3.6-m telescope at La Silla was used to obtain 20-minute exposures in both B- and I-band, as well as spectroscopy for the surrounding objects in Oct. 1997 by P. Shaver and I. Hook. There is no obvious optical identification for J06587−5558, but the bright elliptical galaxy $5''$ to the east (galaxy A in Fig. 4) was confirmed as a cluster member ($z \sim 0.293$).

If the source is in the cluster then the lack of any optical identification with cluster galaxies suggests that it may possibly be a radio relic 62×19 kpc in extent. Diffuse radio relics of the type seen in A3667 and A2256 are known to be polarised with very steep spectra, though without significant depolarisation. For instance, the relics (G and H) in A2256 are polarised at a 20% level at 1.4 GHz

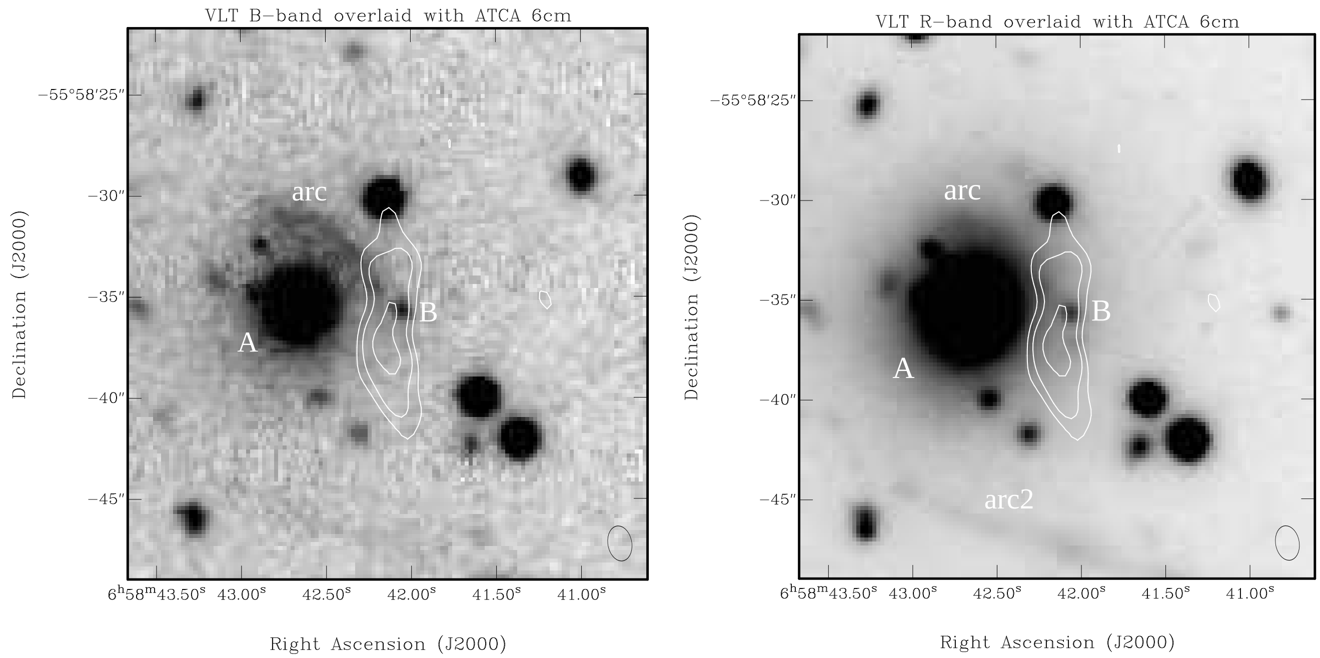

Figure 4. A high-resolution 4800 MHz contour map overlaid on VLT B-band (*left*) and R-band (*right*) images; the measured seeing was $0.75''$ FWHM. Galaxy A is a cluster member, while faint galaxy B is the brightest object which falls within the radio source envelope. Two possible gravitational lens arcs associated with galaxy A are marked. Contours are at 0.2, 0.4, 0.8 mJy/beam, and the rms noise of the image is $\sigma = 65\mu$Jy. The radio beam ($1.7'' \times 1.2''$) is shown in the lower right-hand corner of each image.

Table 1. Properties of the peculiar radio source

Position (J2000)	RA = 06 58 42.1
	Dec = −55 58 37
Total extent	$15'' \times 4.5''$
Linear size	62×19 kpc ($z = 0.296$)
	103×31 kpc ($z = 3.5$)
$S_{1.3}$ (note a)	37 ± 2 mJy
$L_{1.4}$ (note b)	9×10^{24} W Hz^{-1} ($z = 0.296$)
	3.5×10^{27} W Hz^{-1} ($z = 3.5$)
$\alpha_{4.8}^{8.8}$ (note c)	-1.5 ± 0.3
$\alpha_{1.3}^{2.2}$ (note d)	-1.0 ± 0.1
Linear pol.(8.8 GHz)	(54 ± 11)%
Linear pol.(4.8 GHz)	(45 ± 9)%
Linear pol.(2.2 GHz)	(4.3 ± 0.5)%
Linear pol.(1.3 GHz)	< 0.5%
RM (note e)	-266 ± 37 radians m^{-2}
PA$_0$ (note f)	$-84° \pm 2°$

[a] Total flux density at 1.3 GHz
[b] Total radio luminosity at 1.4 GHz (rest frame)
[c] Average spectral index across the source between 4.8 and 8.8 GHz
[d] Average spectral index across the source between 1.3 and 2.2 GHz
[e] Rotation measure across the source with a resolution of $2.7'' \times 2.2''$
[f] Intrinsic position angle of the E-vector

(Röttgering et al. 1994). However, these relics are much larger in spatial extent (~ 1 Mpc) and more diffuse than J06587−5558.

The source appears to be embedded in the outer parts of the radio halo, with its long axis approximately tangential to the X-ray contours. It is conceivable that J06587−5558 is just an enhanced part of the radio halo where the local magnetic field is strong and well organised, as in the case of a shock seen in the plane of compression. Figure 3 shows that the magnetic field vectors are well aligned with the direction of the source elongation over at least the southern half of the source. The surface brightness of J06587−5558 is roughly 100 times that of the halo, so the magnetic field in the source would need to be at least 10 times greater than the large scale cluster field, which is still reasonable.

5 BEHIND THE CLUSTER?

We have also searched in the near infrared in case the optical emission is obscured by dust, or the object is at a redshift such that most of the optical emission above the 4000 Å break has been shifted into the infrared. We observed the field for 4.5 hrs on 1999 November 23 with the infrared camera CASPIR on the ANU 2.3m telescope at Siding Spring Observatory. No infrared counterpart was found to a limiting magnitude of H ~ 20.

If the source is behind the cluster, then it may be a radio galaxy at high redshift. The alignment of the magnetic field with the elongation of the source is consistent with that of large-scale jets. The depolarisation and slight flattening of the spectrum near the position of the possible optical counterpart (Fig. 1) may also be consistent with a core-jet structure in which the core is often depolarised with a flatter spectrum. High-redshift radio galaxies are known to have steep spectral indices ($\alpha < -1$). However, in a polarisation study of a sample of high redshift radio galaxies, Carilli et al. (1997) found a maximum integrated polarisation of ~ 20% at 8.2 GHz. Hence, if this source is a high redshift radio galaxy, it is exceptional in terms of its polarisation properties.

Alternatively, J06587−5558 could also be the gravitationally lensed part of a background jet since small parts of a jet can sometimes be highly polarised and the more polarised parts tend to have a steeper spectrum. If it is just part of the jet, then we do not expect

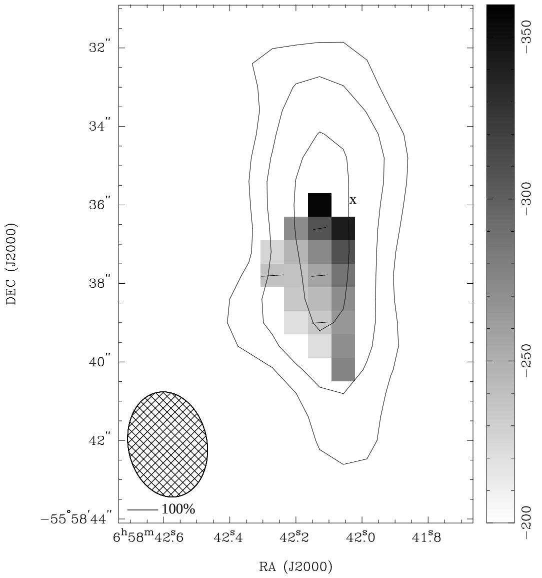

Figure 3. A total intensity contour image at 8768 MHz overlaid on a greyscale rotation measure image. The E-vectors are shown rotated back to the intrinsic position angles of the linearly polarised emission at 8768 MHz, and their lengths give the percentage linear polarisation (the vector length corresponding to 100% polarisation is shown in the bottom left-hand corner). The contours are $(3, 6, 12) \times \sigma$, where the rms noise of the image is $\sigma = 50\mu$Jy. The beam is shown in the bottom left-hand corner ($2.7'' \times 2.0''$) and the location of the possible optical counterpart (Sec. 6) is marked with a cross.

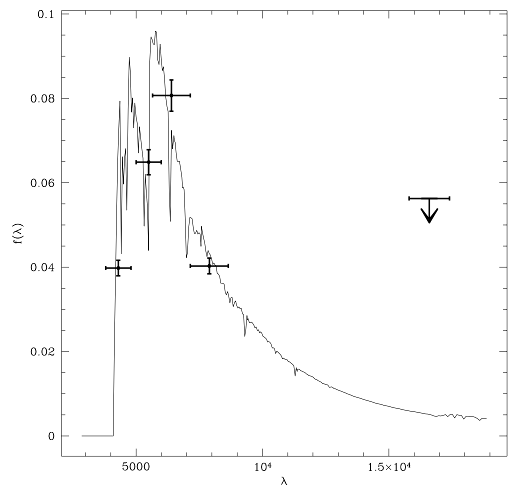

Figure 5. A synthetic SED (solid curve) corresponding to an elliptical galaxy at $z = 3.5$ is plotted along with the observed broad-band fluxes ($f(\lambda)$ has units of erg s^{-1} cm^{-2} Å^{-1}) against the wavelength in the observer's frame of reference. The vertical error bars correspond to the photometric errors and the horizontal bars correspond to the width of the filters in wavelength.

to find an optical identification at the position of the radio emission. The cluster 1E0657−56 is one of the most massive clusters known; it can act as an effective gravitational lens. To produce the orientation of the source, it is necessary to have another lens to the other side of the source. The elliptical cluster galaxy (A) to the east of the source could act as such a counterweight.

6 OPTICAL IDENTIFICATION FROM THE VLT

VLT images of the field of J06587−5558 were obtained by Mehlert et al. (private communication) with UT1 in the B, g, R and I bands during the FORS1 commissioning in December 1998. Exposure times were 10 minutes and the measured seeing was $0.75''$ FWHM. These images revealed a faint possible identification (B), embedded in the halo of the galaxy (A) to the east of the source (Fig. 4), at 06 58 42.04, −55 58 35.8 (J2000).

The astrometric transfer to the deep VLT images was done using the publicly available SuperCOSMOS scans of the red (IIIaF) sky survey plate of Field 162 from the UK/AAO Schmidt telescope. The formal fit error on this plate is given as $0.13''$ rms in each coordinate. The accuracy of radio-optical registration was confirmed to be $\leq 0.2''$ by overlaying the full resolution ATCA 3 cm images of two tailed cluster source in 1E 0657−56 on the VLT image. The displacement of galaxy B from the axis and centroid of the radio emission ($\sim 0.6''$) is real, and therefore casts doubt on any possible association.

To estimate fluxes in the VLT B, g, R and I bands, we extracted a patch $\sim 26'' \times 26''$ (128^2 pixels) centred on the nearby elliptical galaxy (A), and fitted a photometric model to the galaxy (A) and to eight compact sources embedded in the extended galaxy profile, including galaxy B. We selected an isolated, bright but unsaturated, star from each image to define the point-spread function (PSF), and utilised the IMFIT package, written by B. McLeod, which has been used to determine photometric models for lensed systems in the CASTLES project (see, e.g., Lehár et al. 2000). We used magnitude zero points kindly provided by S. Seitz. The quality of the fits was high, yielding estimated uncertainties of ~ 0.05 mag. Apparent magnitudes of galaxy B thus measured in B, g, R and I bands are listed in Table 2 along with the upper limit in H band.

The steepness of the radio spectrum suggests that J06587−5558 is unlikely to be a quasar or a Seyfert galaxy. Radio galaxies are identified with giant elliptical galaxies. It has been shown by Scarpa & Urry (2000) that there is no fundamental difference between the optical properties of radio and non-radio emitting elliptical galaxies except that the probability of an elliptical galaxy hosting a radio source is proportional to the square of its optical luminosity. Assuming that galaxy B is an elliptical, we found a solution for the photometric redshift, $z_{\rm ph} = 3.5 \pm 0.1$, using the public domain photometric redshift program HYPERZ (Bolzonela et al. 2000). A synthetic Spectral Energy Distribution (SED) corresponding to an elliptical galaxy (Bruzual & Charlot 1993) was fitted to the broad band magnitudes taking into account the dust absorption through the galaxy itself using the reddening law of Calzetti et al. (2000), and the continuum absorption by the Lyman forest using estimates for Lyman-α and Lyman-β line blanketing by Madau (1995) and zero flux throughput below the Lyman limit. The SED fit to the observed broad band flux is given in Fig. 5. At $z \sim 3.5$, the source would have $M_R \sim -21.3$ and $L_{1.4\,{\rm GHz}} \sim 3.5 \times 10^{27}$ W Hz^{-1}, typical of a classical FR II radio galaxy.

Finally, we examine the significance of galaxy B being within the radio contours of J06587−5558. In the small $\sim 26'' \times 26''$ patch centred on galaxy A, we found 10 faint objects in the B-band image with magnitudes similar to galaxy B. Hence the probability of finding an object like galaxy B within the second radio contour ($\sim 8'' \times 3''$) by chance is $\sim 36\%$ which shows that the coincidence is not of high significance.

Table 2. Optical and near infrared magnitudes of galaxy B. The magnitudes have been corrected for Galactic extinction.

$m_{\rm B}$	$m_{\rm g}$	$m_{\rm R}$	$m_{\rm I}$	$m_{\rm H}$
24.75±0.05	23.84±0.05	22.79±0.05	22.92±0.05	>20

We also note that there are two arc-like features, one long straight arc to the south and another arc to the north-west of galaxy A, a confirmed cluster member. The long arc is seen in the R-band ('arc2' in Fig. 4) as well as the I-band image and it is most likely to be a gravitational arc. The other arc is most prominent in the B-band image ('arc' in Fig. 4). It could be a gravitational arc or a tidal feature as a result of merging. If it is a gravitational arc, then it makes the lensing scenario given at the end of Sec. 5 more plausible since the radio contour would then be traversing the caustics. If it is a merging signature, then it lends support to the presence of shocks and hence the cluster relic scenario (Sec. 4).

7 CONCLUSIONS

We have found an unusual extended radio source with a steep radio spectrum and extreme integrated linear polarisation (Table 1). After eliminating the likelihood that the source is Galactic, we have considered three possible explanations for these unusual properties:

- Gravitational lens

J06587−5558 is the lensed fragment of a jet belonging to a distant radio galaxy. This would explain the high polarisation since small regions of radio galaxies are known to have high polarisation. The proximity of the bright elliptical (A), the presence of the rich cluster and the arcs in the immediate surroundings lend support to this scenario.

- $z = 3.5$ radio galaxy with no lensing

The optical identification (galaxy B) is offset from the radio central axis, and the probability of a chance coincidence of galaxy B falling within the radio contours of J06587−5558 is high. If galaxy B is not the true identification then the true identification must be even fainter which means that it is a radio galaxy at $z > 3.5$. In either case, the high polarisation is very unusual since high redshift radio galaxies are not known to have such high polarisation (Carilli et al. 1997).

- Cluster relic

The presence of the rich cluster, the nearby bright elliptical galaxy (A) and the possible tidal feature shows that J06587−5558 maybe in regions of shocks which favour the formation of cluster relics. However, known cluster relics are larger in spatial extent, more diffuse and without significant depolarisation.

We are grateful to Isobel Hook for taking the ESO 3.6-m data, Stella Seitz for providing the VLT magnitude zero points, and Hans Böhringer for obtaining a spectrum of one of the galaxies. We acknowledge the use of the HYPERZ photometric redshift program (http://webast.ast.obs-mip.fr/hyperz/), and the use of the KARMA package (http://www.atnf.csiro.au/karma) for the overlays.

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